(In)direct Detection of *Boosted* Dark Matter

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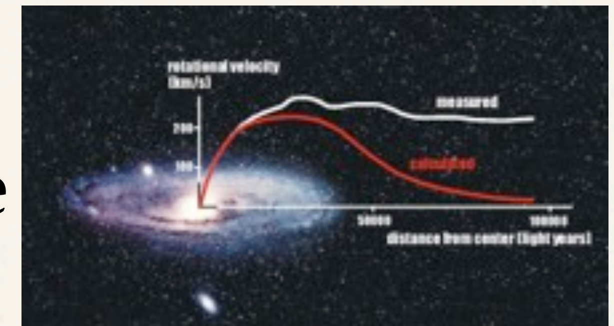
arxiv:1405.7370, K. Agashe, YC, L.Necib and J.Thaler

Introduction

- Conventional Concepts of DM

- **Dark Matter:** 85% of matter, preponderance of gravitational evidence



- **Compelling paradigm:** DM is composed of massive particles

  E.g. Simplest, best studied: One specie of WIMP with Z_2 parity, $\Omega_{\rm DM}$ set by thermal freezeout of WIMP annihilation to SM states

➡ Current-day DM is non-relativistic, $v_{\rm DM,0} \simeq \mathcal{O}(10^{-3})$

➡ **Designs of DM detection experiments**

- ⋆ Indirect detection: nearly-at-rest annihilation/decay to SM states
- ⋆ Direct detection: small nuclear recoil energy $E_R \sim \frac{\mu^2}{m_N} v_{\rm DM,0}^2$

Introduction: Beyond the "Conventional/Minimal"

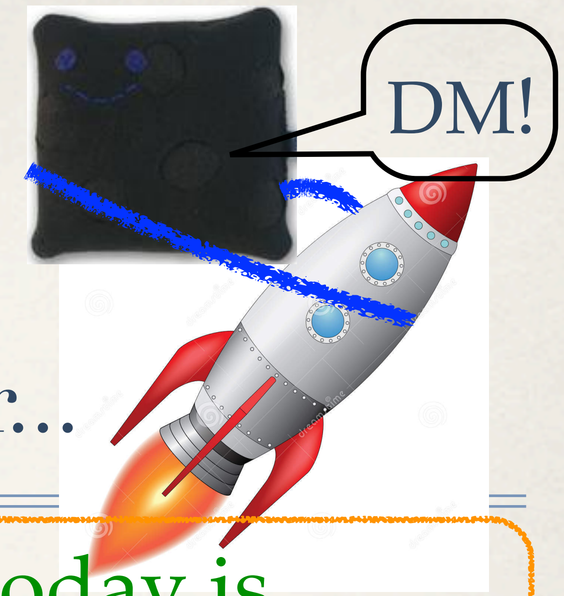
- **Status of DM detections:**
  - No convincing signal (anomalies: PAMELA, AMS-2, GC γ excess...)
  - Constraints getting stronger: e.g. LUX, CDMS, FERMI, HESS, LHC...

Conventional/Minimal thermal WIMP DM $\in$ Nature?

1. Yes, just keep looking (e.g. Higgs portal DM...)
2. No, give up WIMP miracle DM (e.g. axion, non-thermal DM)
3. **Yes and No: non-minimal dark sector: DM annihilate into dark states** (decay to SM, stable --secluded from both direct/indirect searches)

- **Philosophical considerations:**
  - SM is non-minimal! Two stable matter components e$^-$, p, mass hierarchy
  - Non-minimal DM?: Existing explorations of **multi-component DM:** e.g. mirror DM, atomic DM, double-disk DM...

Boosted Dark Matter



- A generic phenomena in non-minimal DM sector...

Novel, generic possibility: A small fraction of DM today is relativistic! from late-time non-thermal processes ➡ Boosted DM!

- **Sources of boosted DM:** non-minimal components/symmetries...
  - DM conversion: $\psi_i \psi_j \to \psi_k \psi_\ell \;\; ; \psi_k \, , \psi_\ell$ lighter (e.g. Belanger, Park, 2011)
  - Semi-annihilation: $\psi_i \psi_j \to \psi_k \phi$, Z_3 DM symmetry (e.g. D'Eramo, Thaler, 2010)
  - Self-annihilation: $3 \to 2 \, , 4 \to 2$ (Carlson, Machacek, Hall 1992, Hochberg et.al 2014)
  - Decay transition: $\psi_i \to \psi_j + \phi$ (e.g. inelastic DM)
  - DM Induced nucleon decay: $p + \psi \to e^+ + \bar{\psi}$ (Davoudiasl et.al 2010, Huang,Zhao,2014)
- **Detection of boosted DM:**
  - **Impact:** reveal novel/non-minimal features of DM sector, in some cases smoking-gun of DM sector (example later...)
  - **Challenge:** conventional DM detections unsuitable, new strategies needed!

"(In)direct Detection of Boosted DM" (arxiv: 1405.7370)

-A Simple Example, Proof of Concept

Outline *(for the rest of the talk)*

- Example Model (2-component DM)
- Thermal Relic Abundances, Current-day Annihilation
- Search Strategies for Boosted DM (Experiments, signal, background)
- Detection Prospects at Present/Future Experiments (SuperK, PINGU…)
- Constraints on the Model
- Conclusions/Outlook

Basic Idea/Assumptions

Consider two species of DM (need not be fermions): ψ_A , ψ_B, $m_A > m_B$

- ψ_A : dominant DM component, no direct (*tree-level*) coupling to the SM,

thermal relic abundance $\Omega_{\rm DM} \approx \Omega_{\psi_{\rm A}}$ set by thermal annihilation

$\boxed{\psi_A \overline{\psi}_A \to \psi_B \overline{\psi}_B}$ ("Assisted freezeout", Belanger, Park, 2011)

-- The same annihilation process in Galactic halo today, non-relativistic ψ_A , produce relativistic ψ_B, with Lorentz factor (boost) $\gamma = \frac{m_A}{m_B}$

- ψ_B : sub-dominant DM, small (non-thermal) fraction: boosted DM!

ψ_B also isolated from the SM? Then in general $T_{\rm DM} \neq T_{\rm SM}$ at ψ_A freeze-out,

$T_{\rm DM}, \Omega_{\rm DM}$ sensitive to other details beyond $\sigma_{A\overline{A} \to B\overline{B}}$ (e.g.reheating, early entropy release...)

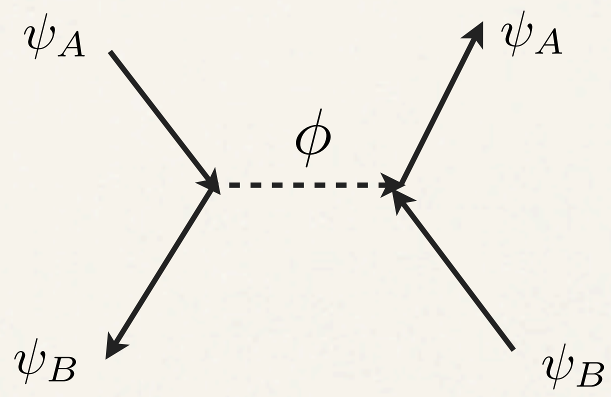
ψ_B has appreciable interaction with the SM: maintain key merit of "WIMP paradigm", neat prediction $\sigma_{\rm ann} \to \Omega_{\rm DM}$

- Offer hope for detecting dark sector: major DM ψ_A can well evade detections...
- ***Direct*** detection of boosted ψ_B via ***indirect*** detection of ψ_A : can be smoking-gun of DM sector! if ψ_B has small thermal abundance, low mass ($\lesssim$ GeV)

A Concrete Model Example

Consider two species of Dirac fermion DM: ψ_A, ψ_B, $m_A > m_B$, stabilized by separate symmetries (e.g. $\mathbb{Z}_2 \times \mathbb{Z}_2$)

- Contact operator $\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2}\overline{\psi}_A\psi_B\overline{\psi}_B\psi_A$, ensure s-wave annihilation of ψ_A to boosted ψ_B, UV completion ☞



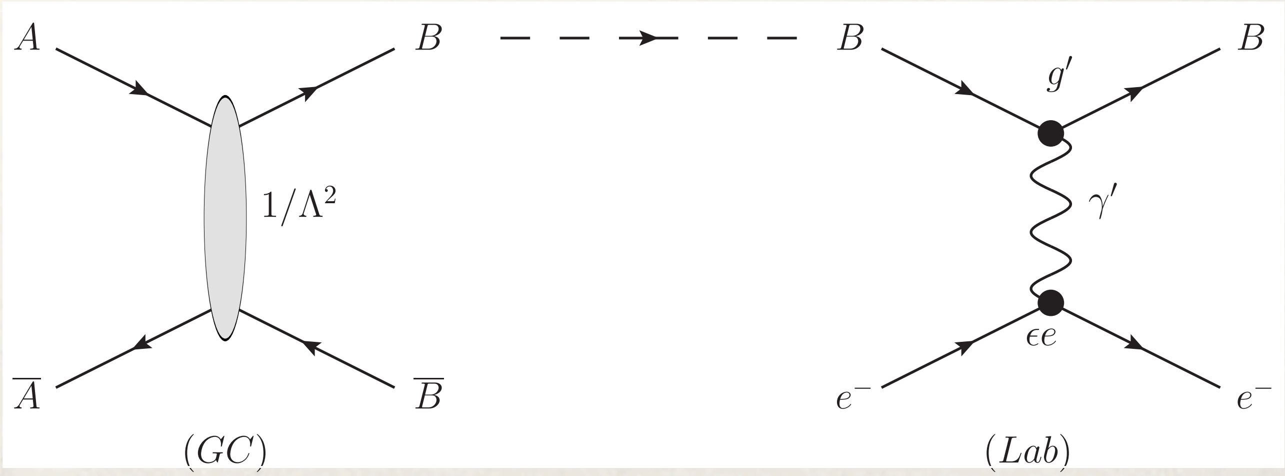
  - The only (tree-level) interaction of ψ_A at low E;
  - Determine Ω_A, dominant DM

- ψ_B charged under a dark broken $U(1)'$, dark photon γ' kinetic mixing with SM photon:

$$\mathcal{L} \supset -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

➡ ψ_B can scatter off terrestrial SM targets, via neutral-current-like process $\psi_B X \to \psi_B X^{(\prime)}$

Processes for (in)direct detection of boosted DM, e.g.:



Model parameter space

defined by 6 parameters: $\{m_A, m_B, m_{\gamma'}, \Lambda, g', \epsilon\}$

- Λ : adjusted to yield the desired DM relic abundance of ψ_A
- Cross-section of $\psi_B X \to \psi_B X^{(\prime)}$ scales homogeneously with g' and ϵ

➡ Dominant phenomenology depends on just mass parameters

- **Detectability:** sufficient large flux of boosted DM, appreciable

scattering rate at detectors,

+ other constraints (more later...)

➡ Focus on low mass DM, with $m_A > m_B > m_{\gamma'}$

Benchmark scales: $m_A \simeq \mathcal{O}(10\ \mathrm{GeV}), \quad m_B \simeq \mathcal{O}(100\ \mathrm{MeV}), \quad m_{\gamma'} \simeq \mathcal{O}(10\ \mathrm{MeV}).$

Thermal Relic Abundance, Present-day Annihilation

Annihilation processes (s-wave): $\psi_A \overline{\psi}_A \to \psi_B \overline{\psi}_B$, $\psi_B \overline{\psi}_B \to \gamma' \gamma'$

Coupled Boltzmann equations:

$$\frac{dn_A}{dt} + 3Hn_A = -\frac{1}{2}\langle \sigma_{A\bar{A}\to B\bar{B}} v \rangle \left(n_A^2 - \frac{(n_A^{\rm eq})^2}{(n_B^{\rm eq})^2} n_B^2 \right),$$

$$\frac{dn_B}{dt} + 3Hn_B = -\frac{1}{2}\langle \sigma_{B\bar{B}\to\gamma'\gamma'} v \rangle \left(n_B^2 - (n_B^{\rm eq})^2 \right) - \frac{1}{2}\langle \sigma_{B\bar{B}\to A\bar{A}} v \rangle \left(n_B^2 - \frac{(n_B^{\rm eq})^2}{(n_A^{\rm eq})^2} n_A^2 \right)$$

ψ_A and ψ_B effectively decouple when $\langle \sigma_{B\bar{B}\to\gamma'\gamma'} v \rangle \gg \langle \sigma_{A\bar{A}\to B\bar{B}} v \rangle$

- easily satisfied, with assumed spectrum $m_A > m_B > m_{\gamma'}$

- In this decoupling limit, Ω_A takes the standard form of WIMP DM:

$$\Omega_A \simeq 0.2 \left(\frac{5 \times 10^{-26}\ {\rm cm^3/s}}{\langle \sigma_{A\bar{A}\to B\bar{B}} v \rangle} \right) \Rightarrow \langle \sigma_{A\overline{A}\to B\overline{B}} v \rangle \approx 5 \times 10^{-26}\ {\rm cm^3/s} \left(\frac{m_A}{20\ {\rm GeV}} \right)^2 \left(\frac{250\ {\rm GeV}}{\Lambda} \right)^4$$

- Ω_B more subtle! $\psi_A \overline{\psi}_A \to \psi_B \overline{\psi}_B$ active, impactful on Ω_B, even after ψ_A freezes out (before ψ_B) with nearly constant Y_A well above $Y_A^{\rm eq}$ at late time

"Balanced Freezeout" of ψ_B

In the limit of $\langle \sigma_{B\bar{B}\to\gamma'\gamma'} v\rangle \gg \langle \sigma_{A\bar{A}\to B\bar{B}} v\rangle$, Y_B approaches asymptotic solution when a balance reaches between ψ_B annihilation ($\psi_B\overline{\psi}_B \to \gamma'\gamma'$) and replenishment from $\psi_A\overline{\psi}_A \to \psi_B\overline{\psi}_B$, i.e. $\frac{dY_B}{dx} \to 0$ when :

$$-\langle \sigma_{B\bar{B}\to\gamma'\gamma'} v\rangle \left(Y_B^2 - (Y_B^{\rm eq})^2\right) \simeq +\langle \sigma_{A\bar{A}\to B\bar{B}} v\rangle \left(Y_A^2 - \frac{(Y_A^{\rm eq})^2}{(Y_B^{\rm eq})^2} Y_B^2\right)$$

VS. conventional freezeout criteria:

$\Gamma \simeq H$

Relic abundance from **"Balanced Freezeout"**:

$$\boxed{\frac{\Omega_B}{\Omega_A} \simeq \frac{m_B}{m_A}\sqrt{\frac{\langle \sigma_{A\bar{A}\to B\bar{B}} v\rangle}{\langle \sigma_{B\bar{B}\to\gamma'\gamma'} v\rangle}}}$$

- ✦ Novel relation of $\Omega \propto 1/\sqrt{\sigma}$, very different from usual $\Omega \propto 1/\sigma$

- ✦ Important input for considering constraints on thermal (non-relativistic) ψ_B :

$$\Omega_B \ll \Omega_A \approx \Omega_{\rm DM} \text{ when } m_B \ll m_A \text{ and/or } \langle \sigma_{B\bar{B}\to\gamma'\gamma'} v\rangle \gg \langle \sigma_{A\bar{A}\to B\bar{B}} v\rangle$$

E.g. at benchmark point: $m_A = 20$ GeV, $m_B = 200$ MeV, $m_{\gamma'} = 20$ MeV, $g' = 0.5$, $\epsilon = 10^{-3}$,

$\Omega_B \simeq 2.6 \times 10^{-6}\,\Omega_{\rm DM}$

Detecting Boosted Dark Matter

- Flux of boosted ψ_B from GC:

$$\frac{d\Phi_{\rm GC}}{d\Omega\, dE_B} = \frac{1}{4}\frac{r_{\rm Sun}}{4\pi}\left(\frac{\rho_{\rm local}}{m_A}\right)^2 J\, \langle \sigma_{A\overline{A}\to B\overline{B}} v\rangle_{v\to 0} \frac{dN_B}{dE_B}$$

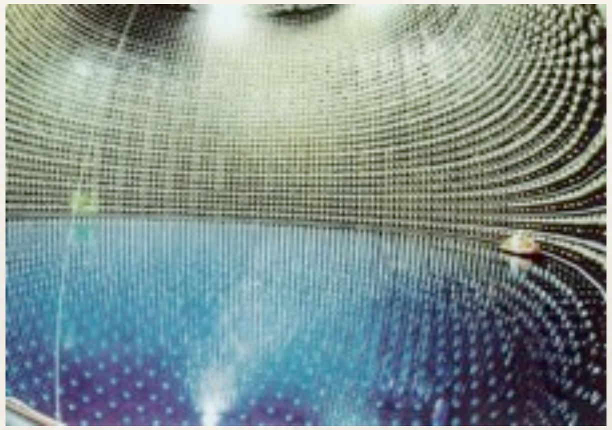
e.g. assuming NFW profile, integrate over 10° cone around GC:

$$\Phi_{\rm GC}^{10^\circ} = 1.6\times 10^{-8}\ {\rm cm}^{-2}{\rm s}^{-1}\left(\frac{\langle \sigma_{A\overline{A}\to B\overline{B}} v\rangle}{5\times 10^{-26}\ {\rm cm}^3/{\rm s}}\right)\left(\frac{20\ {\rm GeV}}{m_A}\right)^2$$

- Rather small flux! ...  ***How to detect it?***

Need: <u>large volume</u>, small background detector, <u>sensitive</u> to scattering $\psi_B X \to \psi_B X^{(\prime)}$ (X, X' : SM states) with energetic ψ_B

 Such experiments already exist!! Neutrino/proton decay detectors: e.g. SuperK: IceCube:



<u>and their upgrades/ extensions (HyperK, PINGU, MICA...)</u> !

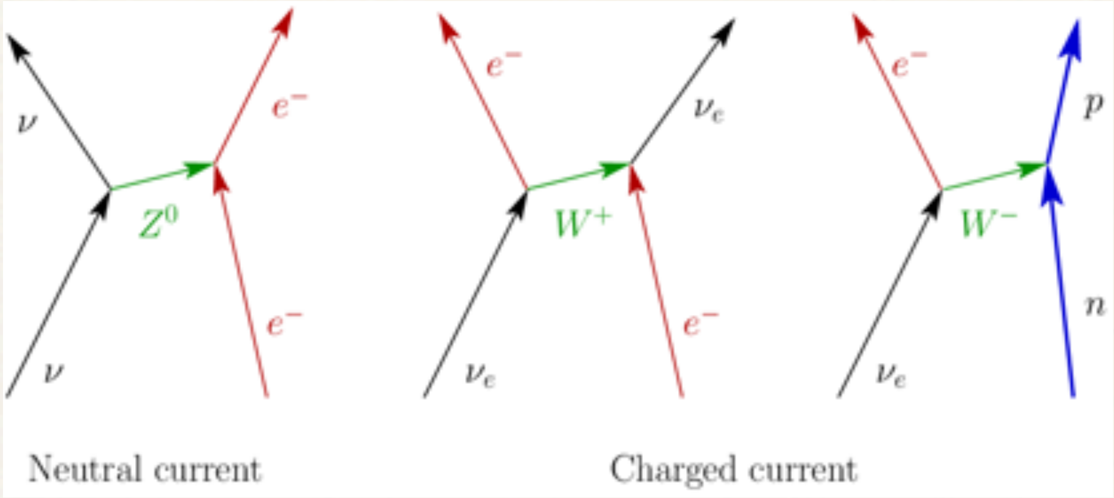
Detection strategy at neutrino detectors:

Cherenkov light from final state charged particles,
must be energetic enough to cross Cherenkov threshold:

$$\text{Water: } \gamma_{\text{Cherenkov}} = 1.51, \qquad \text{Ice: } \gamma_{\text{Cherenkov}} = 1.55.$$

- Scattering processes of atmospheric neutrinos (background to boosted DM):

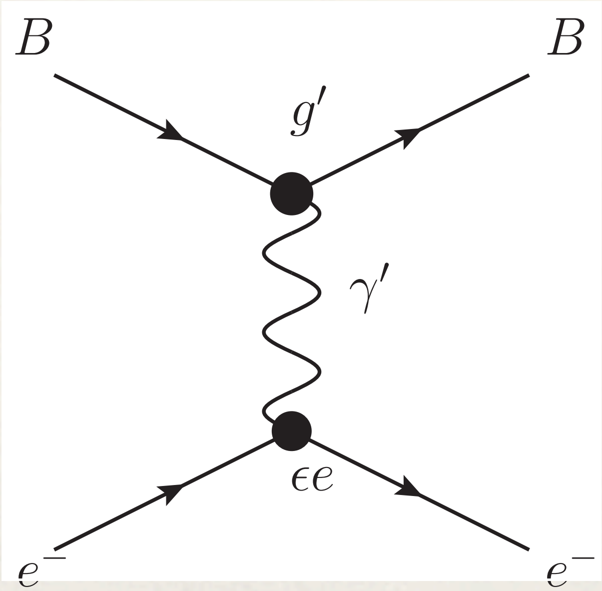
E.g.



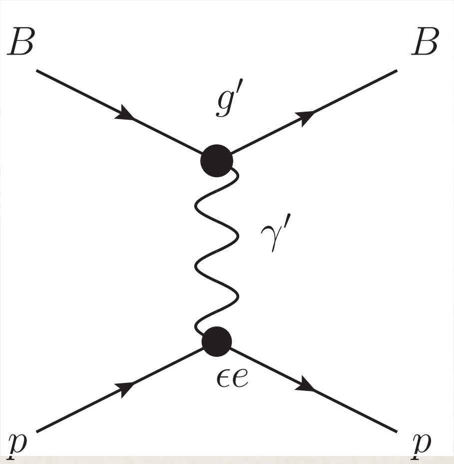
+other final states: μ^-, hadronic inelastic

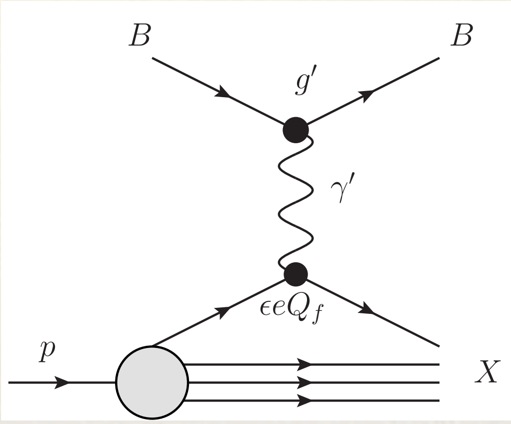
- Detection channels for boosted DM ψ_B: neutral-current type, no μ^- final state

Leading signal: single e^-

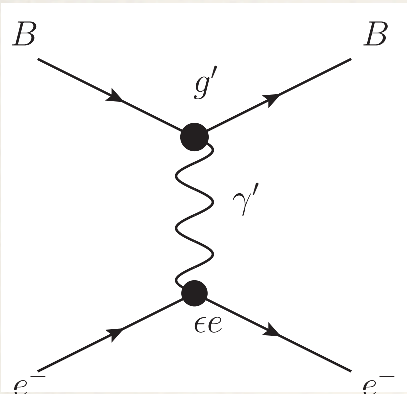


Subleading: hadronic channels ($\sigma_{p,\text{tot}} \sim \frac{m_p}{m_e}\sigma_{e^-,\text{tot}}$, but for the model with t-channel light γ', E_{transfer} typically too small to cross Cherenkov/DIS threshold)





Kinematics, Rate of $\psi_B e^- \to \psi_B e^-$ Scattering at Detectors



4-momenta of incoming and outgoing particle (lab frame):

$$\text{Incident } \psi_B:\ p_1 = (E_B, \vec{p}), \qquad \text{Scattered } \psi_B:\ p_3 = (E'_B, \vec{p}\,'),$$
$$\text{Initial } e:\ p_2 = (m_e, 0), \qquad \text{Scattered } e:\ p_4 = (E_e, \vec{q}).$$

- Mono-energetic boosted ψ_B from ψ_A annihilation: $E_B = m_A$

- Maximal energy of scattered e^- by pure kinematics:

$$E_e^{\max} = m_e \frac{(E_B + m_e)^2 + E_B^2 - m_B^2}{(E_B + m_e)^2 - E_B^2 + m_B^2}$$

- Minimum detectable energy of scattered e^- :

$E_e^{\min} = \max\{E_e^{\text{thresh}}, \gamma_{\text{Cherenkov}} m_e\}$ E_e^{thresh}: analysis threshold at experiment in consideration

Viable phase space: $E_e^{\max} \geq E_e^{\min}$

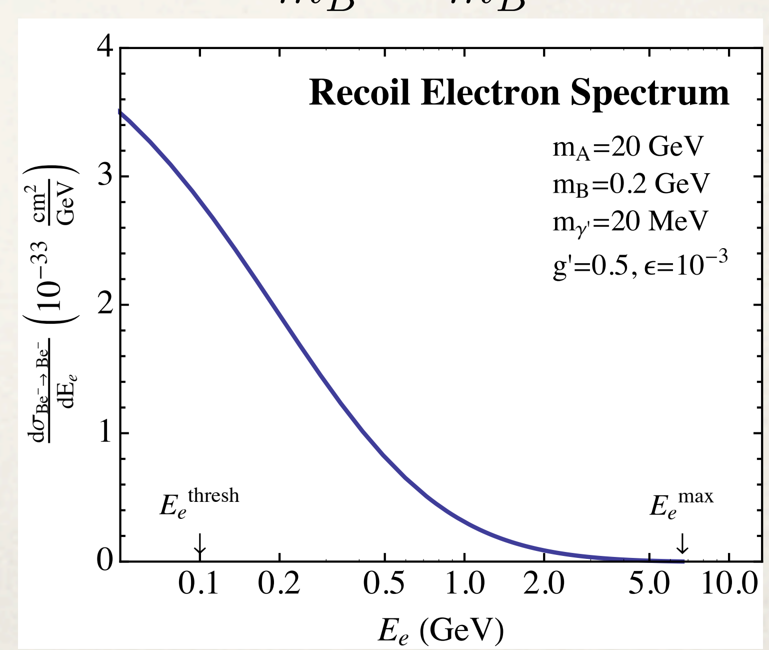
- In terms of boost factors: $\gamma_e^{\max} = 2\gamma_B^2 - 1, \gamma_e^{\min} = \frac{E_e^{\min}}{m_e}, \gamma_B = \frac{E_B}{m_B} = \frac{m_A}{m_B}$

- Differential cross-section: peaks at low E_e

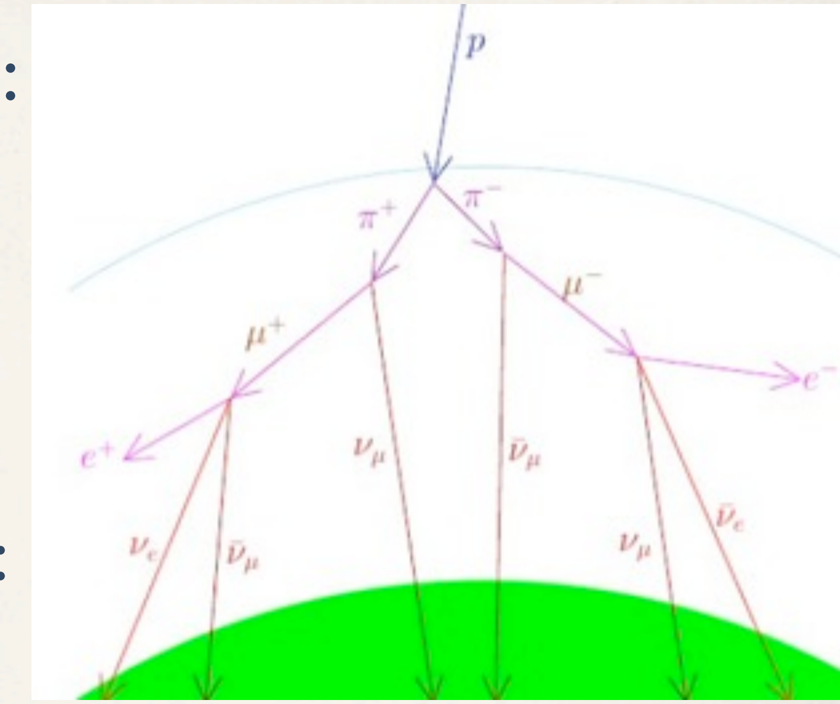
$$\frac{d\sigma_{Be^- \to Be^-}}{dt} = \frac{1}{8\pi} \frac{(\epsilon e g')^2}{(t - m_{\gamma'}^2)^2} \frac{8E_B^2 m_e^2 + t(t+2s)}{\lambda(s, m_e^2, m_B^2)},$$

Integrated (assume $E_e^{\text{thresh}} = 100$ MeV):

$$\sigma_{Be^- \to Be^-} = 1.2 \times 10^{-33}\ \text{cm}^2 \left(\frac{\epsilon}{10^{-3}}\right)^2 \left(\frac{g'}{0.5}\right)^2 \left(\frac{20\ \text{MeV}}{m_{\gamma'}}\right)^2$$



Background and its Rejection Strategies



- Major background from atmospheric neutrinos:
  cosmic ray interacts with the Earth's atmosphere
  - Spectrum peaks $\sim$1 GeV, falls as $E^{-2.7}$ at high E
  - $\nu_e : \nu_\mu \sim 1:2$ ($\pi^\pm$ cascade decay)
  - Leading background for our signal $\psi_B e^- \to \psi_B e^-$:
    CC scattering $\nu_e n \to e^- p$, with p undetected

For $\mathcal{O}(1\ \text{GeV})$ neutrinos, $\sigma_{\rm CC} \approx 0.8 \times 10^{-38}\ \text{cm}^2 \left(\frac{E_\nu}{\text{GeV}}\right)$

$\sigma_{\rm CC} < \sigma_{Be^- \to Be^-}$ at benchmark point, but $\nu_{\rm atm}$ has much larger flux than boosted DM...

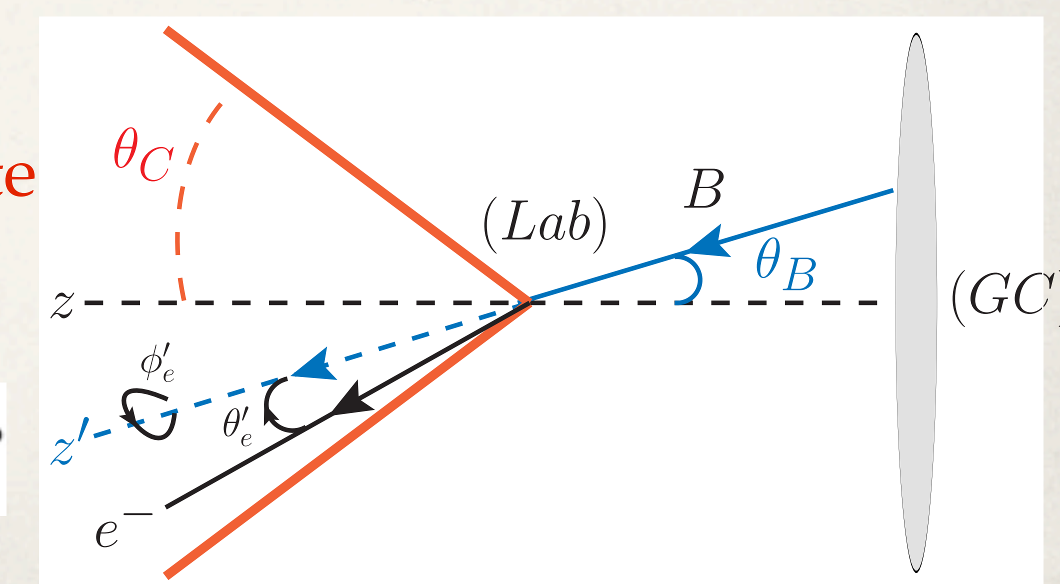
- How to separate boosted DM signal from neutrino background?

Discriminants for S vs. B:

1. ***Angular restriction:*** Boosted DM has a definite direction-the GC, vs. $\nu_{\rm atm}$ is nearly isotropic.

Impose that detected e^- falls within a cone with half-opening angle θ_C w.r.t. the GC.

θ_C determined by optimizing significance



Discriminants for S vs. B (➡ Background rejection algorithm)

2. *Energy restriction:* Boosted DM is mono-energetic ($E_B = m_A$), vs. continuous energy of $\nu_{\rm atm}$ spectrum.

➡ A correlation between E_e and $\cos\theta'_e$: $\cos\theta'_e = \frac{(m_A + m_e)}{\sqrt{m_A^2 - m_B^2}}\frac{\sqrt{E_e - m_e}}{\sqrt{E_e + m_e}}$

- Typical resolution of neutrino detectors may not be fine enough to make use of this, low E threshold also needed.

The above #1, #2: Favor detectors with excellent angular/E resolution + low threshold.

3. *Absence of muon excess:* Signal process $\psi_B e^- \to \psi_B e^-$ has no correlated muon signature, vs. $\nu_{\rm atm}$ CC process $\nu_e n \to e^- p$ accompanied by $\nu_\mu n \to \mu^- p$.

4. *Multi-ring veto:* Signal $\psi_B e^- \to \psi_B e^-$ leads to single-ring e^- events only, vs. $\nu_{\rm atm}$ CC process can lead to multi-ring events (e.g. p , $\pi^\pm$ Cherenkov rings)

The above #3,#4 can also distinguish boosted DM signal from neutrinos from other BSM models: WIMP DM annihilation in the GC.

5. *Solar neutrino/muon veto:* solar neutrinos dominate background $\lesssim 20$ MeV, neutrino bkg from muons decaying within detector: 30-50 MeV

➡ Impose a cut $E_e > 100$ MeV in our analysis to avoid complications.

Detection Prospects at Present/Future Experiments

Candidate experiments: Large volume detectors for neutrino/proton decay

Summary of representative experiments:

Experiment	Volume (MTon)	$E_e^{\rm thresh}$ (GeV)	$\theta_e^{\rm res}$ (degree)
Super-K	2.24×10^{-2}	0.01	3°
Hyper-K	0.56	0.01	3°
IceCube	10^3	100	30°
PINGU	0.5	1	23°(at GeV scale)
MICA	5	0.01	30°(at 10 MeV scale)

(MICA: still speculative)

- IceCube (KM3NeT, ANTARES): larger volume, but $E_e^{\rm thresh}$ high, $\theta_e^{\rm res}$ large

(In our model typically $E_e \lesssim 1$ GeV due to light t-channel γ' in param region of interest)

- **Future** low energy extension of IceCube:
  - ★ PINGU: threshold not ideal, but has sensitivity
  - ★ ? MICA: low enough threshold, and large volume *(still speculative)*
- Super-K/Hyper-K: smaller volume, but low $E_e^{\rm thresh}$, excellent $\theta_e^{\rm res}$

  + Super-K has 10-yr data available!

- Recent proposals based on large-volume Liquid Ar: LAr TPC, GLACIER, ionization based, no Cherenkov threshold limit, hadronic channel possible...

Event Selection

- Our analysis for sensitivity: ***Cut-and-count based,*** simple (vs. MVA)

- **Impose search cone θ_C to isolate events from GC** (reduce bkg by θ_C^2)

  Optimum θ_C determined by maximizing signal significance (≈10°, later...)

  Also limited by experimental resolution! ➡ $\theta_C = \max\{10^\circ, \theta_e^{\rm res}\}$

- **Energy selection:** *Ideally:* adjust E range based on $E_e^{\max}$ for given m_A and m_B, push analysis threshold $E_e^{\min}$ as low as possible. ➡ *best sensitivity*

  Our *conservative* approach: take the standard Super-K events categories, without finer energy binning, easy to use existing data...

  Fully-contained single-ring electron events at Super-K: ☞ $$\begin{aligned}\text{Sub-GeV: } &\{100\ \text{MeV}, 1.33\ \text{GeV}\},\\ \text{Multi-GeV: } &\{1.33\ \text{GeV}, 100\ \text{GeV}\},\end{aligned}$$

  - Use both sub- and multi-GeV categories for Super / Hyper-K and MICA
  - PINGU: higher $E_e^{\rm thresh}$, cannot reconstruct Cherenkov rings, nor separate e- from μ- near threshold ➡ Use only multi-GeV+multi-ring, μ- like events

Signal Rates

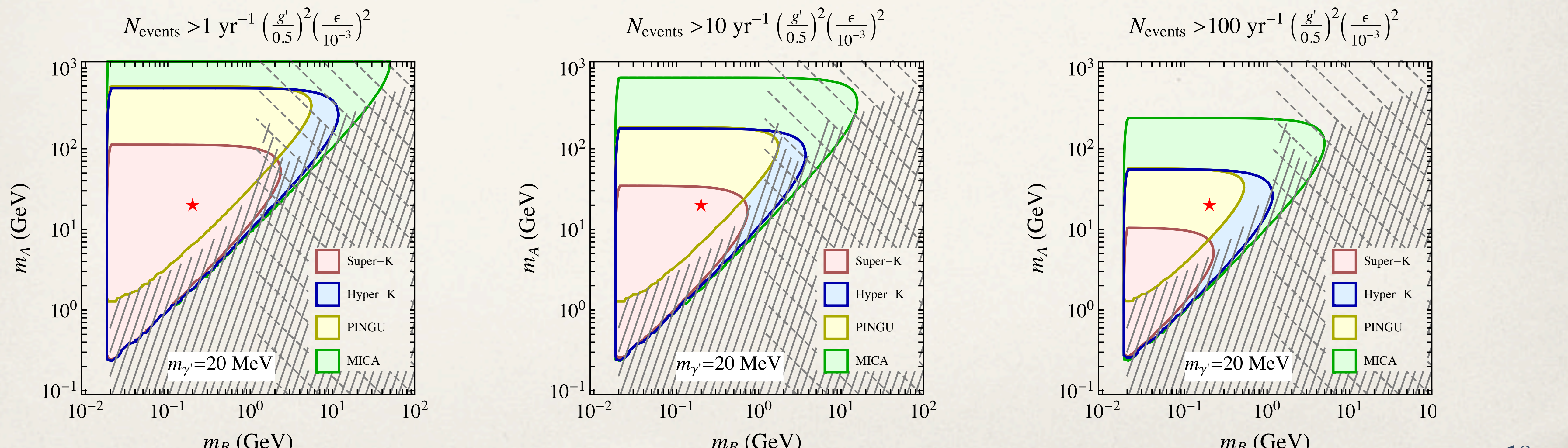
Imposing θ_C and energy range requirements, number of signal events:

$$
\begin{aligned}
N^{\theta_C}_{\rm signal} &= \Delta T\, N_{\rm target} \left(\Phi_{\rm GC} \otimes \sigma_{Be^- \to Be^-}\right)\Big|_{\theta_C} \\
&= \frac{1}{2}\Delta T \frac{10\,\rho_{\rm Water/Ice} V_{\rm exp}}{m_{\rm H_2O}} \frac{r_{\rm Sun}}{4\pi} \left(\frac{\rho_{\rm local}}{m_A}\right)^2 \langle \sigma_{A\bar{A}\to B\bar{B}} v \rangle_{v\to 0} \\
&\quad \times \int_0^{2\pi} \frac{d\phi'_e}{2\pi} \int_{\theta'_{\rm min}}^{\theta'_{\rm max}} d\theta'_e \, \sin\theta'_e \frac{d\sigma_{Be^-\to Be^-}}{d\cos\theta'_e} \int_0^{\pi/2} d\theta_B \sin\theta_B \, 2\pi J(\theta_B) \Theta(\theta_C - \theta_e)
\end{aligned}
$$

E.g. Number of signal events per year with $\theta_C = 10^\circ$, sub-GeV+multi-GeV:

$$
\frac{N^{10^\circ}_{\rm signal}}{\Delta T} = 25.1 \text{ year}^{-1} \left(\frac{\langle \sigma_{A\bar{A}\to B\bar{B}} v\rangle}{5\times 10^{-26}\ {\rm cm^3/s}}\right) \left(\frac{20\ {\rm GeV}}{m_A}\right)^2 \left(\frac{\sigma_{Be^-\to Be^-}}{1.2\times 10^{-33}\ {\rm cm^2}}\right) \left(\frac{V_{\rm exp}}{22.4\times 10^3\ {\rm m^3}}\right)
$$

Number of signal events in various experiments (m_A-m_B plane):



Background Rates, Signal Significance

- **Background rates**

Atmospheric neutrino background measured by Super-K over 10.7 yrs

Super-K data: fully contained single-ring 0-decay electron events *(all sky)*:

$$\text{Sub-GeV:} \quad \frac{N_{\rm bkgd}^{\rm all\ sky}}{\Delta T} = 726 \ {\rm year}^{-1} \left(\frac{V_{\rm exp}}{22.4 \times 10^3 \ {\rm m}^3} \right)$$

$$\text{Multi-GeV:} \quad \frac{N_{\rm bkgd}^{\rm all\ sky}}{\Delta T} = 197 \ {\rm year}^{-1} \left(\frac{V_{\rm exp}}{22.4 \times 10^3 \ {\rm m}^3} \right)$$

Background events inside the search cone θ_C: $N_{\rm bkgd}^{\theta_C} = \frac{1-\cos\theta_C}{2} N_{\rm bkgd}^{\rm all\ sky}$

e.g. For $\theta_C = 10^\circ$ (Super-K):

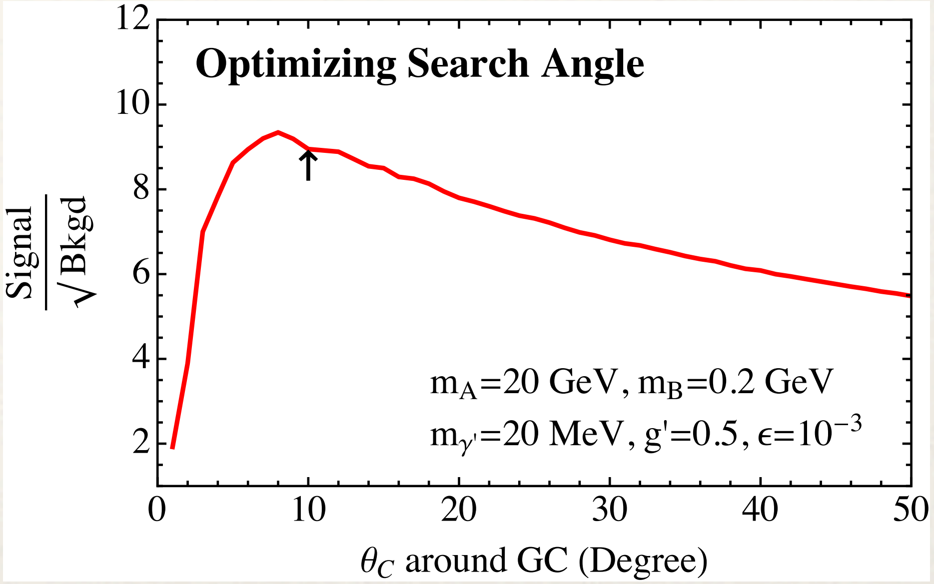
$$\text{Sub-GeV:} \quad \frac{N_{\rm bkgd}^{10^\circ}}{\Delta T} = 5.5 \ {\rm year}^{-1}.$$

$$\text{Multi-GeV:} \quad \frac{N_{\rm bkgd}^{10^\circ}}{\Delta T} = 0.35 \ {\rm year}^{-1}.$$

- **Signal significance:**

$$\mathrm{Sig}^{\theta_C} \equiv \frac{N_{\rm signal}^{\theta_C}}{\sqrt{N_{\rm bkgd}^{\theta_C}}}$$

Search cone angle determined by maximizing Sig^{θ_C}

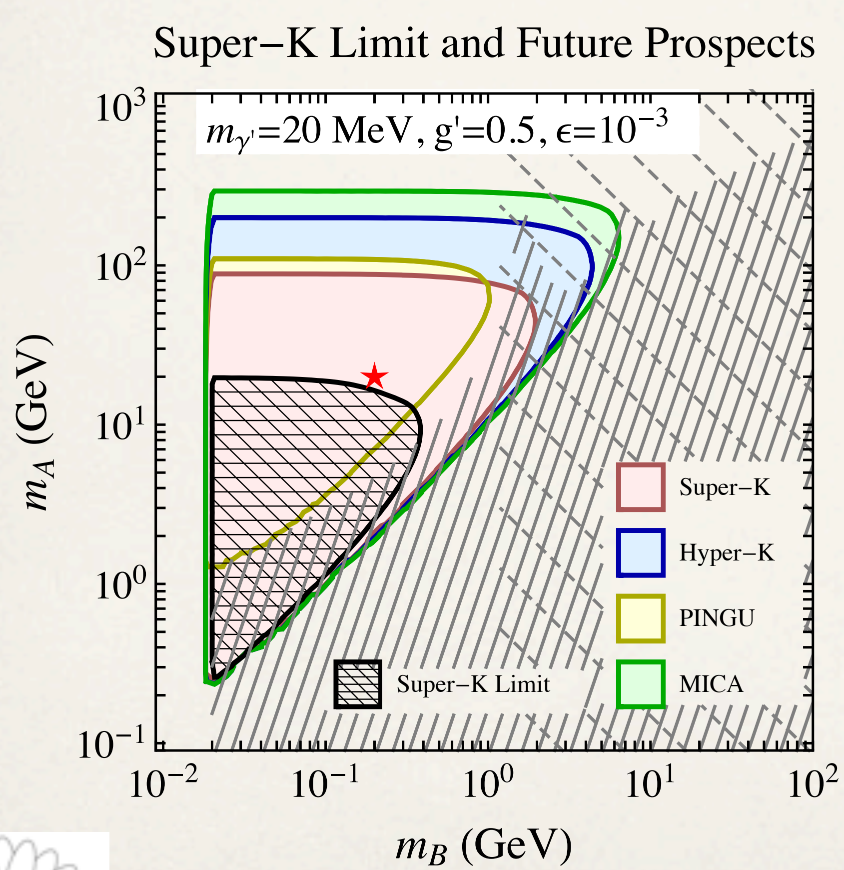


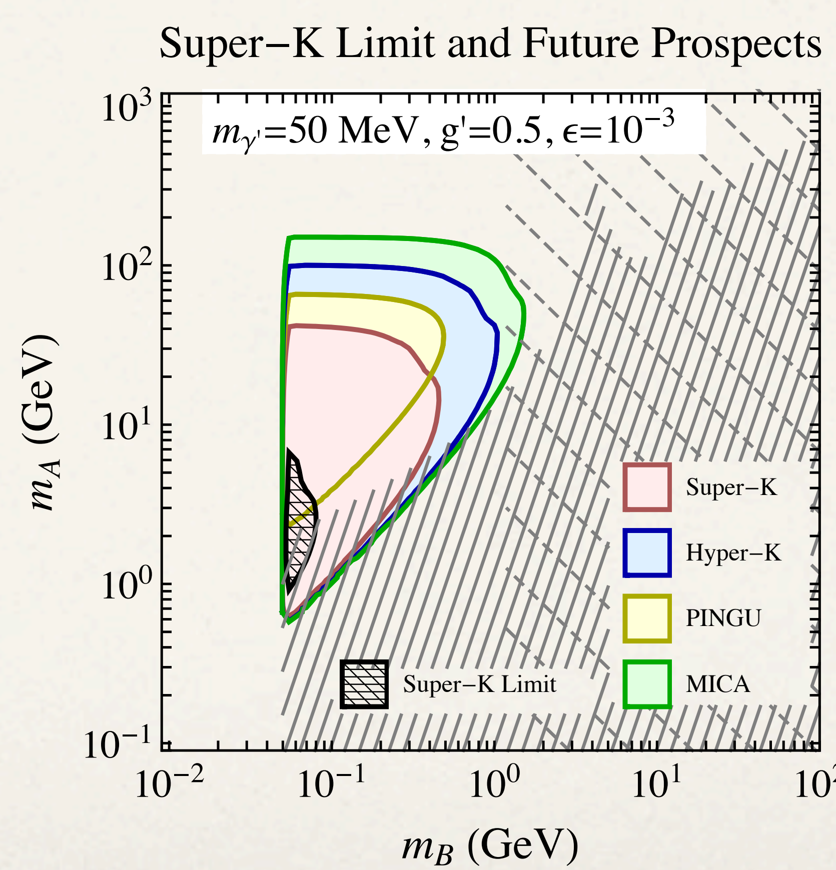
Estimated Experimental Reach, Limits

- Impose 2σ exclusion limit using SuperK 10-year all-sky data
- Analyze 2σ signal reach w/optimal search cone around GC direction,

  For fair comparison of different experiments: assume same event selection, same exposure time as Super-K, + multi-GeV, μ-like for PINGU

E.g. Signal sensitivity at experiments, Limits from SuperK (m_A-m_B plane):





Light grey lines: model-dependent limits (to explain next...)

Substantial reach for boosted DM! Super-K already promising

Other Existing Constraints-1 (model-dependent)

- ***Limits on dark photon:*** dark photon searches → $m_{\gamma'} \gtrsim \mathcal{O}(10\ \mathrm{MeV})$ and $\epsilon \lesssim 10^{-3}$ assuming leading decay mode $\gamma' \to e^+e^-$, for $m_{\gamma'} \gtrsim \mathcal{O}(10\ \mathrm{MeV})$ beam-dump experiments → $\epsilon \gtrsim 10^{-5}$;

  Our benchmark: $m_{\gamma'} = 20\ \mathrm{MeV}$ and $\epsilon = 10^{-3}$, allowed, and of interest for muon g-2

- ***Direct detection of (thermal) non-relativistic major DM*** ψ_A : ψ_A can scatter off nuclei via ψ_B loop, so subject to conventional DM direct detection at e.g. XENON, LUX, CDMS. Enough suppression from higher-dim operator $\psi_A\overline{\psi}_A\psi_B\overline{\psi}_B$ + loop factor; inelastic splitting may further help

✓ • ***Direct detection of (thermal) non-relativistic*** ψ_B: large ψ_B-nucleon scattering cross section $\sigma_{Bp\to Bp} = 4.9 \times 10^{-31}\ \mathrm{cm}^2 \left(\frac{\epsilon}{10^{-3}}\right)^2 \left(\frac{g'}{0.5}\right)^2 \left(\frac{20\ \mathrm{MeV}}{m_{\gamma'}}\right)^4 \left(\frac{m_B}{200\ \mathrm{MeV}}\right)^2$

  scaled down by small abundance ☞ $\sigma^{\mathrm{eff}}_{Bp\to Bp} = \frac{\Omega_B}{\Omega_{\mathrm{DM}}}\sigma_{Bp\to Bp}$

  - **O(GeV)**: best constraints from CDMSLite, Damic; stringent, inelastic DM helps
  - **Sub-GeV:** <u>our most favored region for signal,</u> can only be constrained by scattering off electrons, only existing limit: XENON10 (2006 with few electron trigger) *(Essig et.al, 2012)* → Constraints are weak *(subsumed by CMB heating limit…)*

Other Existing Constraints-2 (model-dependent)

- ***Indirect detection of (thermal) non-relativistic*** ψ_B :

  the annihilation $\psi_B\overline{\psi}_B \to \gamma'\gamma'$ + subsequent decay $\gamma' \to e^+e^-$ lead to potential indirect detection signal (positron, γ-ray). Constraints from AMS-02, Fermi etc. rather weak: small abundance/rate, large bkg uncertainties/analysis cut for sub-GeV, O(GeV) energies. *(CMB limit stronger...)*

✓ • ***CMB constraints on thermal*** ψ_B ***annihilation:*** with $m_B \lesssim \mathcal{O}(1\ \mathrm{GeV})$, ψ_B annihilation in the early universe is subject to constraints from CMB heating *(Madhavacheril et.al 2012)*. Bound is imposed on the injection power:

$$p_{\mathrm{ann},\psi_\mathrm{B}} = f_{\mathrm{eff}} \frac{\langle \sigma_{B\overline{B}\to\gamma'\gamma'} v\rangle}{m_B} \left(\frac{\Omega_B}{\Omega_{\mathrm{DM}}}\right)^2 \simeq f_{\mathrm{eff}} \langle \sigma_{A\overline{A}\to B\overline{B}}\rangle \frac{m_B}{m_A^2}$$

suppressed by m_B^2/m_A^2 relative to the bound for major DM

Sommerfeld enhancement due to light γ' also included (not significant)

➡ Favors large m_A/m_B ratio, consistent with optimizing boosted DM signal

- ***BBN Constraints on thermal*** ψ_B annihilation: only hadronic final states (n, p, π) lead to constraints comparable/stronger bound than CMB, but not possible for $m_{\gamma'}$ of $\mathcal{O}(10\ \mathrm{MeV})$

- ***DM search at colliders***: weak, since ψ_B interacts w/SM by light mediator

Conclusions, Outlook

❖ **We presented a novel DM scenario**:

✓ Thermal WIMP paradigm, ✓ Evade conventional DM detection bounds

+ *Boosted* DM signal, detectable at large volume neutrino / proton decay experiments (example: a two-component DM model)

❖ **Boosted DM**: generic in DM scenarios beyond the single WIMP paradigm (non-minimal components / symmetry, and more...)

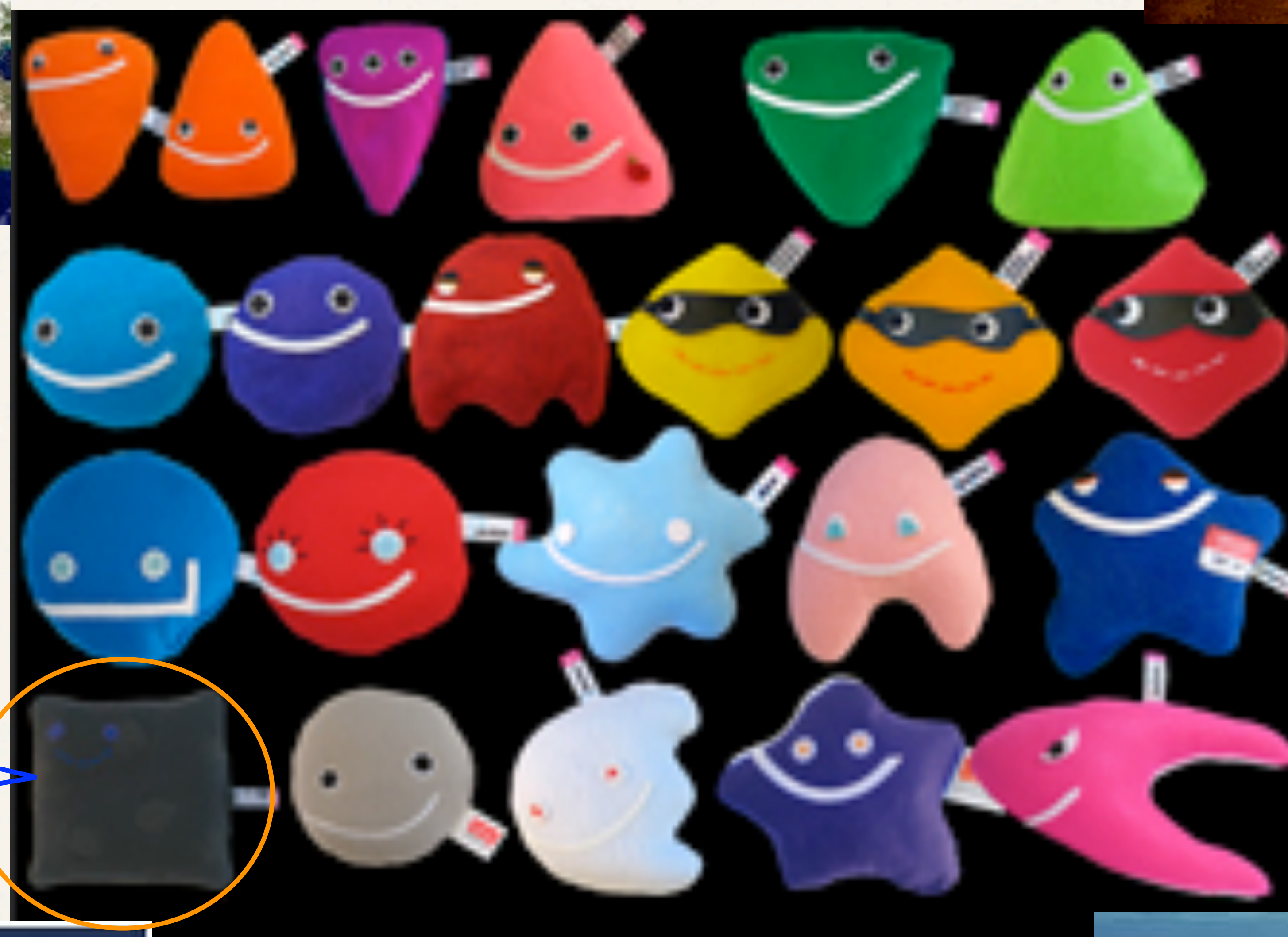
Other example: semi-annihilating DM, 3→2 self-annihilating SIMP...

❖ **Variation based on the example model**: if both ψ_A and ψ_B are charged under $U(1)'$, and $m_A > m_{\gamma'} > m_B$, boosted DM from $\psi_A\overline{\psi}_A \to \gamma'\gamma'$ then $\gamma' \to \psi_B\overline{\psi}_B$; interesting possibility: fraction decay ➡ $\gamma' \to \mathrm{SM\,SM}$, explain GC γ-ray excess...

❖ **Other Possible Signatures/Phenomenology**

- Detecting hadronic final states with: proton tracks, ionization (liquid Ar)
- ψ_A has non-negligible solar-capture rate ➡ boosted DM from the sun
- If ψ_B (interacts via light γ') is a sizable fraction of DM (asymmetric DM) ➡ (partially) self-interacting DM (cusp-core, too-big-to-fail?...)

A "Particle Zoo" for the Dark Matter Sector?



I have friends!

New Phenomenology, New Search strategies needed

Boosted DM an example!